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A1540-53, An Eclipsing X-ray Binary Pulsator

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ABSTRACT

We have observed an eclipsing X-ray binary pulsator consistent with the location of A1540-53. The source pulse period was 528.93±0.10 seconds. The binary nature is confirmed by a Doppler curve for the pulsation period. The eclipse angle of $30.5^{\circ} \pm 3^{\circ}$ and the 4 h transition to and from eclipse suggest an early type, giant or supergiant, primary star.

I. INTRODUCTION

The X-ray source A1540-53 was within the field of view of the GSFC cosmic X-ray spectroscopy experiment aboard OSO-8 for 9 days in August and September, 1976. During this interval, X-ray emission from this region was seen to exhibit all the characteristics of an eclipsing X-ray binary pulsator. Ariel V has also detected pulsations from the source A1540-53 (Davison 1976). This paper will present evidence which confirms the pulsations and establishes the binary nature of the source, and will discuss the characteristics of the system.

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II. OBSERVATIONS

The observations were split between a pointed argon proportional counter with a 3° FWHM field of view and a small-angle scanning xenon proportional counter with a 5° FWHM field of view. Rates from the two detectors are recorded every 0.160 sec. Pravdo (1976) has given a full description of the experiment.

Between Aug 24.5-27.1, 1976, 3U1538-52 and A1540-53 were the only known sources within the field of the argon counter. For the remainder of the observations, the data also were confused to varying degrees by Cir X-1 and MX 1553-54. Figure 1 shows the intensity observed by the argon counter corrected for the aspect of A1540-53 after background subtraction. The source exhibited an extended low intensity phase lasting approximately 55,000 sec. The softness ratio of the X-ray emission after background subtraction is also plotted in Figure 1 where the extended low is used as background for the rest of the emission. For $\sim$ 15,000 sec before and after minimum there is a pronounced hardening of the spectrum, i.e., the extended low is 85,000 sec long for X-rays below 4 keV. The uncertainty in the background level is equal to the intensity at the center of the extended low.

A Fast Fourier Transform of the X-ray flux following the recovery from the extended low revealed a periodicity of 528.4 sec in the data. The data were folded and the resulting light curve is shown in Figure 2. The period and light curve of the pulsations agree with those observed by Ariel V for A1540-53 (Davison 1976). If the intensity for the extended low is taken as background, the pulsed fraction is 0.62. Normalizing for the position of A1540-53, the average intensity over this background is 3.85 x 10^{-10} ergs/cm^{2}-sec between 2-6 keV, approximately 6 times the intensity observed by Davison (1976) and 2.5 times the strength of 3U1538-52 (Giacconi *et al*. 1974). One of these sources may have been observed by Cruddace *et al*. (1972) at an intensity 50 times that of 3U1538-52.

Pulsations were found to be present at all times that A1540-53 was in the field of view except during the apparent eclipses. Data were analyzed for periodicity on 9 consecutive days and the results are tabulated in Table 1. The data indicate a four day periodicity to the pulse period, with a lack of pulsations every fourth day. Refinement of the pulse period and the binary orbital parameters was achieved by folding five days of data from the xenon detector on the pulse period after correcting the arrival times of photons for light travel time across an assumed circular binary orbit. Folds were carried out for trial values of the pulse period and of the orbital parameters and each light curve was tested against the hypothesis of a constant intensity. For a periodic source with a constant pulse profile, the maximum χ^2 will result from the correct values of the varied parameters. An analysis of the data in this manner resulted in the values for the pulse period, orbital period, a sin i, and zero phase of the orbit given in Table 1.

The errors on the parameters in Table 1 can be estimated with several procedures. First, we can calculate the standard deviation of the peak χ^2 value based on the observed counting rate. Then, from the χ^2 vs. parameter curves, we can find the range of parameters with χ^2 within 3σ of the peak value. Alternatively, we can study the duty cycle of the light curve as a function of the folding period. The duty cycle will be minimized for the correct period and increase monotonically away from this period. This effect can be treated analytically (Pravdo, 1977). Both these procedures indicate that the errors quoted in Table 1 are 2-3 sigma errors. Lastly, the errors on the pulse period can be considered qualitatively by noting how large an error would result in the first pulse being out of phase with the last pulse in the fold by more than 0.1 of a pulse period. The errors in Table 1 are greater than or equal to the error expected by this criterion.

The spectrum for the source accumulated by the argon counter following the end of the extended low is shown in Figure 3 where we have again used the extended low as background. The spectrum is well fit with a power-law of number index 1.2 ± 0.2 with absorption by cool material with $N_H = 3.2 \pm 1.0 \times 10^{22}$ atoms/cm^2 consistent with the spectrum of A1540-53 (Davison 1976). Thermal bremsstrahlung models did not yield acceptable fits to the data. A spectrum accumulated during two 15,000 s intervals immediately before and after the eclipse of the > 4 keV X-rays is also plotted in Figure 3. There is a substantial increase in the low energy absorption. This spectrum could be fit with the same power law used for the high state spectrum with a column density N_H of $3.1 \pm 1.0 \times 10^{23}$ atoms/cm^2.

TABLE 1

Pulsation and Orbital Properties

	TIME INTERVAL	PULSED PERIOD (sec)
August	25.45 - 26.15	extended low - no pulsations detected
	26.3 - 27.0	528.4 ± .5
	27.0 - 28.0	528.8 ± .3
	28.0 - 29.0	529.3 ± .3
	29.0 - 30.0	no pulsations detected
	30.0 - 31.0	528.4 ± .3
	31.0 - 31.99	529.1 ± .3
September	1.0 - 2.0	529.5 ± .3
	2.0 - 3.0	no pulsations detected

Estimates of Parameters

Pulse Period	528.93 ± .10 sec
Orbital Period	3.75 ± .15 days
a sin i	53 ± 15 lt-sec
Phase zero of orbit	August 25.8 ± .1, 1976 JD2443016.3 ± .1

III. DISCUSSION

The galactic plane near $\ell^{II} = 320^{o}$ contains a number of X-ray sources, so it is difficult for the GSFC detectors on OSO-8 to isolate specific sources. Therefore, we rely on source identifications made by other observers to define our observations. The Ariel V data have shown that the source A1540-53 is distinct from 3U1538-52 on the basis of positional discrepancy between these two sources (Davison 1976). We cannot distinguish between these two sources on the basis of position, but the agreement between the periodicity discovered in our data and that for A1540-53 (Davison 1976) leaves no doubt that we have observed A1540-53 and not 3U1538-52. Our observations are totally consistent with identifying A1540-53 as an eclipsing X-ray binary pulsator. The Ariel V data supports this conclusion. An extrapolation of the 3.75 day binary period predicts an eclipse centered at day 253.8 of 1975. Ariel V data show no pulsations near this time (Davison 1976).

As we have noted, the eclipse (as defined by the X-rays above 4 keV) is $55 \pm 5 \times 10^3$ secs in duration. Below 4 keV the eclipse lasts $85 \pm 5 \times 10^3$ sec, suggesting the primary star is surrounded by an extensive envelope. The length of these eclipses imply minimum radii for the primary star and its envelope of 8.2 and 12.0 $R_\odot$ respectively. For all possible inclinations, the primary star's radius is greater than half of the separation of the two stars. The uncertainty in (a sin i) allows a range of 4-24 $M_\odot$ for the mass function of the system. If the primary is a main sequence star, we can relate its mass to its radius by two independent methods.

In terms of the eclipse angle θ_e and the separation of the two stars r, the radius of the primary R_1 is given by $R_1 = r(\sin^2\theta_e \sin^2 i + \cos^2 i)^{.5}$. Using $M_1 + M_x = 4\pi^2 r^3/GP^2$ where M_1 and M_x are the masses of the primary and compact stars respectively and P is the binary orbital period, we find

$$\frac{R_1}{R_\odot} \geq 4.8 \left(\frac{M_1 + M_x}{M_\odot}\right)^{1/3}. \tag{1}$$

For main sequence stars (Mihalas 1968)

$$\log \frac{R}{R_\odot} = 0.63 \log \left(\frac{M}{M_\odot}\right). \tag{2}$$

For a reasonable range of M_x ($< 4\ M_\odot$) and M_1, equation (1) results in values of R_1 at least a factor of 1.5 greater than values obtained from equation (2). For a given mass, the primary star is significantly larger than that expected for a main sequence star. We therefore conclude that the primary star must be a giant or supergiant. In this sense, A1540-53 is similar to SMC X-1, Vela XR-1, and Cen X-3, all of which have optically identified supergiant primaries.

Other pulsators with supergiant companions are thought to accrete material from a stellar wind as opposed to Roche lobe overflow. The critical radius R_c for the Roche lobe is given by $R_c \leq r\ \left[.38 + .2 \log\ (M_1/M_x)\right]$ (Pachzynski 1971). The condition that $R_1 < R_c$ would restrict r to between 19 - 43 $R_\odot$.

The luminosity of A1540-53 between 2-20 keV is $1.7 \times 10^{37}\ (\frac{d}{11})^2$ ergs/sec where d is the distance to the source in kpc and 11 kpc is an estimate of the source distance based on N_H. This luminosity is $.25(\frac{d}{11})^2$ times the luminosity of Cen X-3 during its high state (as measured by OSO-8 from 2 - 20 keV). The luminosity of a neutron star accreting from a stellar wind is proportional to $\dot{M}_w/r^2\ V_w^{\ 4}$ where V_w is the wind velocity at the neutron star and $\dot{M}_w$ is the mass loss rate of the primary. Therefore, the relatively low luminosity of A1540-53 could result from a lower mass loss or a greater value of $r^2 V_w^{\ 4}$.

The A1540-53 eclipse transitions extend to an angle of $\sim 48^\circ$, significantly greater than the eclipse angle of 30.5°. The angle to which the Cen X-3 transitions extend varies, but during high states the transitions have been observed to extend to $\sim 48^\circ$ (Schreier <u>et al</u>., 1972). This angle is determined by $L/n^2r^2 \propto (rV_w^{\ 2}\ \dot{M}_w)^{-1}$ (Pringle, 1973). (Hatchett and McCray

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For main sequence stars (Mihalas 1968)

$$\log \frac{R}{R_\odot} = 0.63 \log \left(\frac{M}{M_\odot}\right). \tag{2}$$

(1977) showed that this depends on the X-ray spectra being similar). If we can generalize from this single well-observed eclipse of A1540-53, then, for these two systems, the products of rV_w^2 and $\dot{M}_w$ are approximately equal. This is consistent with the difference in luminosities if rV_w^2 is $1.6(11/d)^{2/3}$ times greater in A1540-53 than in Cen X-3 while $\dot{M}_w$ is less by the same factor. This smaller mass loss for A1540-53 may indicate the primary is less massive and/or less evolved than Krzeminski's star.

The addition of A1540-53 increases the number of X-ray pulsators with well-defined binary periods to five. The pulse periods range from 0.7^s to 529^s and the binary periods from 1.7 days to 8.96 days. Lea (1976) attempted to correlate pulse and binary periods on the assumption that the pre-collapse star rotated at the binary period. A1540-53 is inconsistent with such a model, as this correlation implies a maximum pulse period of $\sim$ 100 s for a system with a binary period of 3.75 days.

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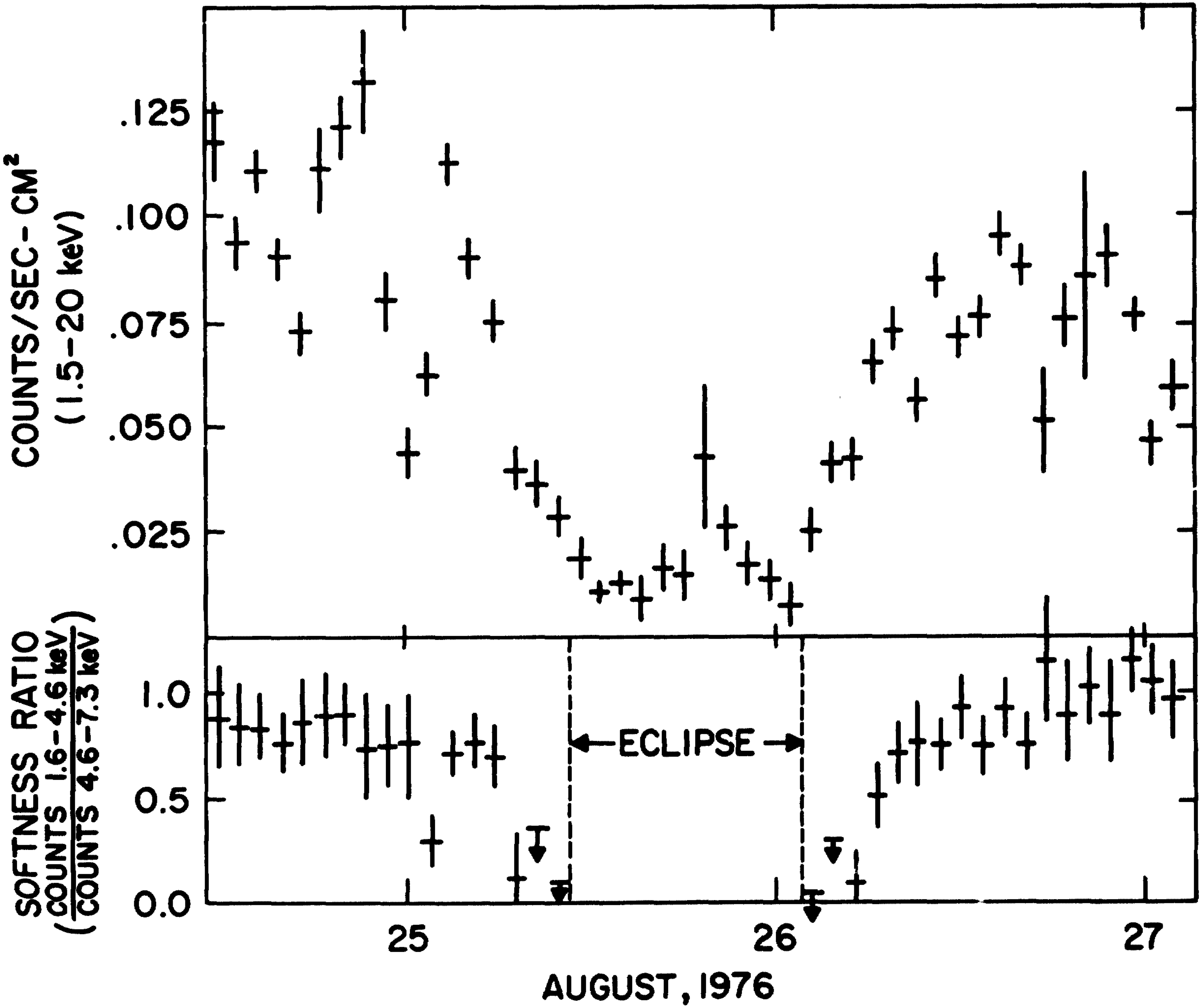
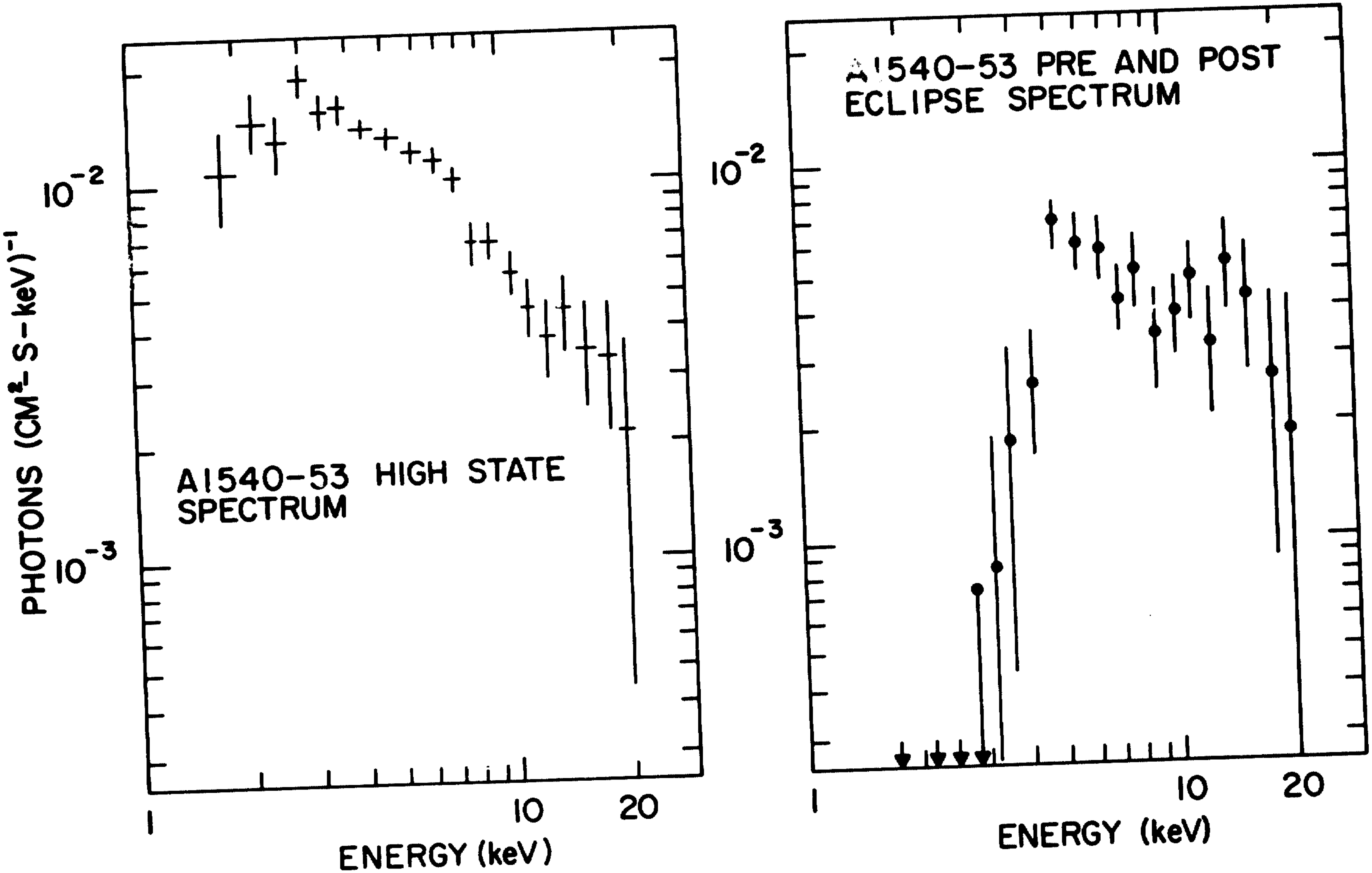
FIGURE CAPTIONS

FIGURE 1: The top histogram shows the 1.5 - 20 keV count rate from A1540-53 corrected for detector pointing after background subtraction. The bottom histogram is a plot of the ratio of counts between 1.6 - 4.6 keV and between 4.6 - 7.3 keV. Low values indicate increased low energy absorption. The spectrum accumulated during the 55000 sec eclipse was used as background. The arrows are two sigma upper limits.

FIGURE 2: Emission from A1540-53 folded on the pulse period. The dashed line indicates the counting rate during the 55,000 sec eclipse.

FIGURE 3: The inferred incident X-ray spectra from A1540-53 for the high state and for transition into and out of eclipse are shown.


COUNTS/SEC-CM²
(1.5–20 keV)
.125
.100
.075
.050
.025
SOFTNESS RATIO
(COUNTS 1.6–4.6 keV / COUNTS 4.6–7.3 keV)
1.0
0.5
0.0
ECLIPSE
25
26
27
AUGUST, 1976



PHOTONS (CM^2- S-keV)$^{-1}$
10^{-2}
10^{-3}
A1540-53 HIGH STATE SPECTRUM
1
10
20
ENERGY (keV)
A1540-53 PRE AND POST ECLIPSE SPECTRUM
10^{-2}
10^{-3}
1
10
20
ENERGY (keV)